

# Phase 1 Space Fission Propulsion Energy Source Design

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**Abstract.** Fission technology can enable rapid, affordable access to any point in the solar system. If fission propulsion systems are to be developed to their full potential; however, near-term customers must be identified and initial fission systems successfully developed, launched, and operated. Studies conducted in fiscal year 2001 (IISTP, 2001) show that fission electric propulsion (FEP) systems with a specific mass at or below 50 kg/kWjet could enhance or enable numerous robotic outer solar system missions of interest. At the required specific mass, it is possible to develop safe, affordable systems that meet mission requirements. To help select the system design to pursue, eight evaluation criteria were identified: system integration, safety, reliability, testability, specific mass, cost, schedule, and programmatic risk. A top-level comparison of four potential concepts was performed: a Testable, Passive, Redundant Reactor (TPRR), a Testable Multi-Cell In-Core Thermionic Reactor (TMCT), a Direct Gas Cooled Reactor (DGCR), and a Pumped Liquid Metal Reactor (PLMR). Development of any of the four systems appears feasible. However, for power levels up to at least 500 kWt (enabling electric power levels of 125-175 kWe, given 25-35% power conversion efficiency) the TPRR has advantages related to several criteria and is competitive with respect to all. Hardware-based research and development has further increased confidence in the TPRR approach. Successful development and utilization of a "Phase 1" fission electric propulsion system will enable advanced Phase 2 and Phase 3 systems capable of providing rapid, affordable access to any point in the solar system.

## I. INTRODUCTION

The fission process was first reported in 1939, and in 1942 the world's first man-made self-sustaining fission reaction was achieved. Creating a self-sustaining fission chain reaction is conceptually quite simple. All that is required is for the right materials to be placed in the right geometry - no extreme temperatures or pressures required - and the system will operate. Since 1942 fission systems have been used extensively by governments, industry and universities. Fission systems operate independently of solar proximity or orientation, and are thus well suited for deep space or planetary surface missions. In addition, the fuel for fission systems (highly enriched uranium) is essentially non-radioactive, containing 0.064 curies/kg. This compares quite favorably to current nuclear systems (Pu-238 in radioisotope systems contains 17,000 curies/kg) and certain highly futuristic propulsion systems

(tritium in D-T fusion systems would contain 10,000,000 curies/kg). An additional comparison is that at launch a typical space fission propulsion system would contain an order of magnitude less onboard radioactivity than did Mars Pathfinder's Sojourner Rover, which used radioisotopes for thermal control. The primary safety issue with fission systems is avoiding inadvertent system start - addressing this issue through proper system design is quite straightforward. The energy density of fission is seven orders of magnitude greater than that of the best chemical fuels, and if properly utilized is more than adequate for enabling rapid, affordable access to any point in the solar system.

Despite the relative simplicity and tremendous potential of space fission systems, the development and utilization of these systems has proven elusive. The first use of fission technology in space occurred 3 April 1965 with the US launch of the SNAP-10A reactor. There have been no additional US uses of space fission systems.

While space fission systems were used extensively by the former Soviet Union, their application was limited to earth-orbital missions. Early space fission systems must be safely and affordably utilized if we are to reap the benefits of advanced space fission systems.

Table 1 gives a partial list of major US space fission programs that have failed to result in flight of a system (Angelo, 1985). There are a variety of reasons why these programs failed to result in a flight. The fact that so many programs have failed indicates that a significantly different approach must be taken if future programs are to succeed. In many cases, space reactor programs were cancelled because the proposed mission was cancelled. However, in many of those cases mission cancellation was partially due to the fact that the reactor required by the mission was taking too long and costing too much to develop. In other cases the lengthy schedule associated with reactor development forced programs to develop and use alternate technologies.

Near-term space fission systems must capitalize on experience gained from previous fission programs. The development of new nuclear technology has historically been costly and time consuming. Nuclear technology developed by previous programs should thus be utilized, and no new nuclear technology should be required. This means that all in-core components should operate within demonstrated fuel burnup capability and demonstrated neutron damage limits for the given reactor environment (temperature, chemistry, power density, etc.). The construction of new nuclear facilities or the extensive modification of existing facilities has historically been costly and time consuming. The development of near-term fission systems should rely on only existing nuclear facilities. Ideally, no new or significantly modified facilities (nuclear or non-nuclear) should be required. Flight qualification of any space system requires an

extensive test program. Near-term fission system flight units must thus be highly testable. Because of the expense and difficulty associated with performing realistic full-power ground nuclear tests, previous programs have considered the option of foregoing full-power ground nuclear testing in favor of a flight test. For example, in Josloff, 1993 (referring to the SP-100 program) it is stated that "There has been recent interest among government agencies in establishing an early flight mission that would provide the catalyst needed to enable confident planning for subsequent operational missions. This first flight would validate the total system performance, obviate the need for costly ground nuclear testing, demonstrate safety features and facilitate safety approval through the INSRP process for the subsequent operational missions." Full power nuclear ground test facility requirements may also dictate that the unit tested on the ground be significantly different than the actual flight unit. Any differences between what is tested and what is flown will limit the benefit from full-power ground nuclear tests. Highly testable systems that utilize established nuclear technology incur the least technical risk if full power ground nuclear testing is not performed. The ability to quickly and affordably establish the safety and reliability of any proposed space fission system will be critical to its programmatic success.

Additional innovative approaches will have to be used to ensure that the next space fission system development program results in system utilization. Safety must be the primary focus of the program, but cost and schedule must also be significant drivers. System performance must be adequate, but the desire to make performance more than adequate should not be allowed to drive system cost and schedule. Near-term space fission systems must be safe, simple, and as inexpensive to develop and utilize as possible.

**TABLE 1.** Partial list of major US Space Fission Programs that Have Failed to Result in Flight of a System.

- |   |  |  |
|---|--|--|
| • Solid-Core Nuclear Rocket Program         | • SNAP-50 / SPUR   | • Advanced Liquid Metal Cooled Reactor         |
| • Medium-Power Reactor Experiment (MPRE)    | • High-Temperature Gas-Cooled Electric Power Reactor (710 Reactor) | • Advanced Space Nuclear Power Program (SPR)   |
| • Thermionic Technology Program (1963-1973) | • SPAR / SP-100  | • Multi-Megawatt Program                       |
| • Space Nuclear Thermal Rocket Program      | • Flight Topaz   | • Thermionic Fuel Element Verification Program |
| • SP-100                                    | • DOE 40 kWe Thermionic Reactor Program                            | • Air Force Bimodal Study                      |

Evaluation of potential first generation (Phase 1) space fission systems began at Los Alamos National Laboratory in 1995 (Houts, 1996). The original evaluations were

based on up to 16 criteria. For the sake of brevity and for more direct applicability to ongoing efforts, the original criteria can be condensed into seven primary criteria:

safety, reliability, testability, specific mass, cost, schedule, and programmatic risk, with scalability

## II. CONCEPT COMPARISON BASED ON SEVEN EVALUATION CRITERIA

The evaluation assumes a required system electrical power of 120 kWe or less – a significant increase in required power could disallow many potential design simplifications, require additional technology development, and reduce system testability. The evaluation also assumes that thermal power will be delivered to the power conversion subsystem at temperatures up to 1300 K. This temperature is near the upper limit of what can be utilized by applicable state-of-the-art power conversion subsystems, thus choosing this temperature helps minimize potential reactor-related impacts on power conversion subsystem operating temperature and performance. Brayton power conversion is chosen as the baseline, although alternatives could be considered for certain systems. Top-level evaluations were previously performed on multiple systems. Observations related to four potential concepts are given: a Testable, Passive, Redundant Reactor (TPRR), a Testable Multi-Cell In-Core Thermionic Reactor (TMCT), a Direct Gas Cooled Reactor (DGCR), and a Pumped Liquid Metal Reactor (PLMR).

considered to be an “other” factor.

## III. DESCRIPTION OF FOUR SYSTEMS

All four reactors could use similar neutron reflectors, ex-core reactor control subsystems, and radiation shields. The primary discriminators between the systems are related to the core design. For the purpose of the comparison, only differences related to core design will be considered. It will be assumed that similar technologies will be employed by all reactors for ex-core subsystems.

### III.A. Testable Passive Redundant Reactor (TPRR)

The TPRR consists of uranium nitride (or uranium dioxide) fuel pins that are conductively coupled to liquid metal heat pipes. Thermal power generated in the fuel is conducted to the heat pipes, where it is transferred to fully independent ex-core heat exchangers. The heat exchangers transfer heat from the heat pipes to the working fluid of the power conversion subsystem. A schematic of the TPRR is shown in Figure 1.

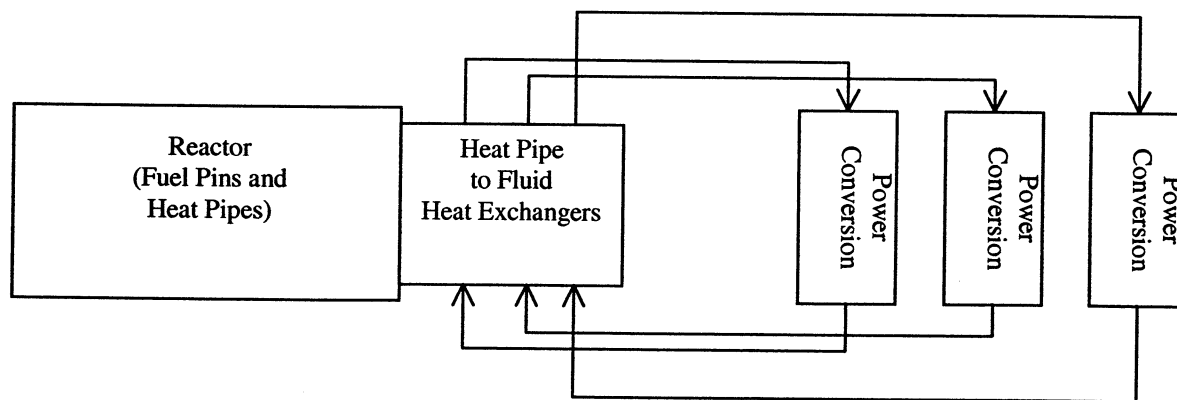
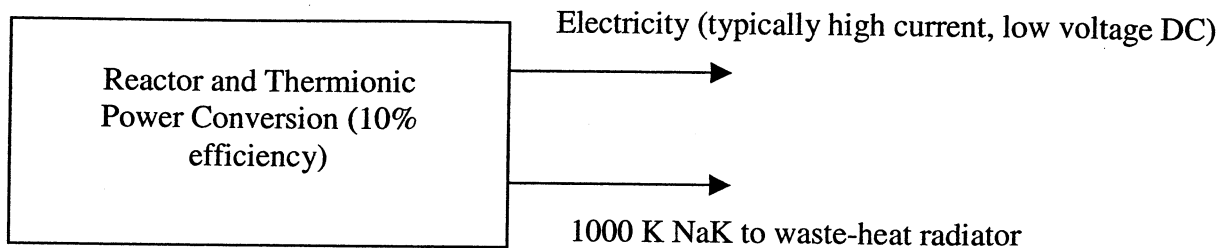


Figure 1. Schematic of the Testable Passive Redundant reactor (TPRR)

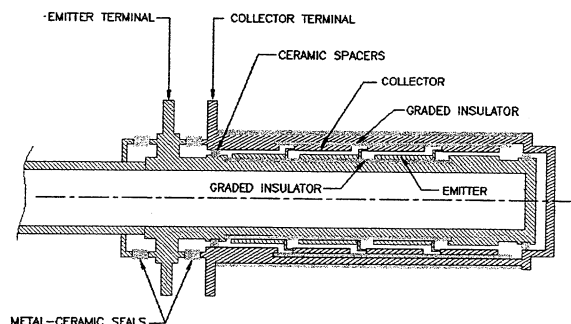
### III.B. Testable Multi-Cell In-Core Thermionic Reactor (TMCT)

The TMCT core consists of approximately 200 testable multi-cell in-core thermionic converters. Uranium dioxide fuel located inside the cylindrical thermionic emitters heats the emitters to approximately 1800 K. Electrons emitted from the emitters travel across a short, cesiated gap to the collectors, which operate at

approximately 1050 K. The collectors are cooled by a pumped NaK loop. Because power conversion occurs within the TMCT core, no ex-core power conversion subsystem is required. A schematic of the TMCT is shown in Figure 2. A schematic of a testable multi-cell in-core thermionic converter is shown in Figure 3 (courtesy General Atomics). The use of an emitter trilayer is a key innovation that enables a testable multi-cell design.



**Figure 2. Schematic of the Testable Multi-Cell In-Core Thermionic Reactor (TMCT).**

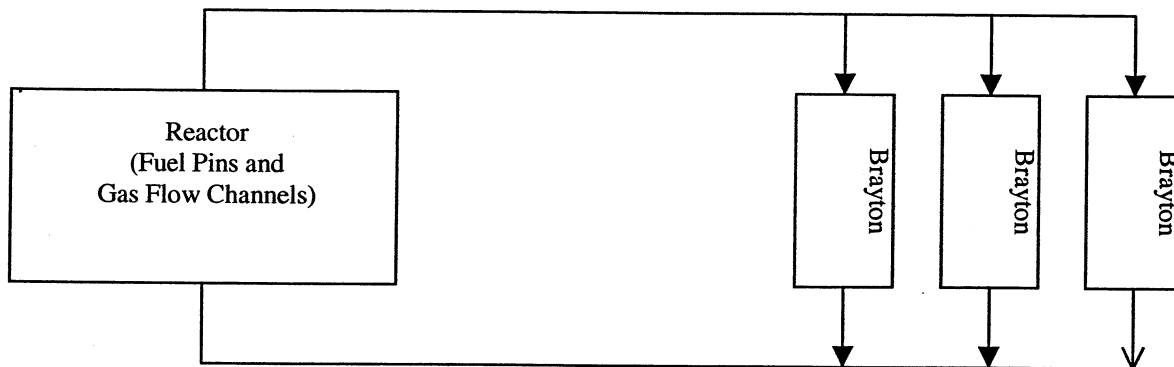


**Figure 3. Schematic of a Testable Multi-Cell In-Core Thermionic Converter (Courtesy General Atomics)**

### III.C. Direct Gas-Cooled Reactor (DGCR)

The DGCR core consists of wire-wrapped fuel pins (or cermet fuel) and He/Xe gas flow passages. Gas exiting the core flows directly to one or more Brayton power

conversion subsystems. Gas flow is maintained by the Brayton power conversion subsystem(s). A schematic of the DGCR is shown in Figure 4.



**Figure 4. Schematic of the DGCR.**

### III.D. Pumped Liquid Metal Reactor (PLMR)

The PLMR core consists of wire-wrapped fuel pins with liquid metal flow passages. The comparison assumes that lithium is chosen as the coolant. If the required system

performance can be achieved using sodium or NaK as the coolant, portions of the evaluation would change. The PLMR also requires a liquid metal pump, a liquid metal / helium separator, and a liquid metal thaw system. A schematic of the PLMR is shown in Figure 5.

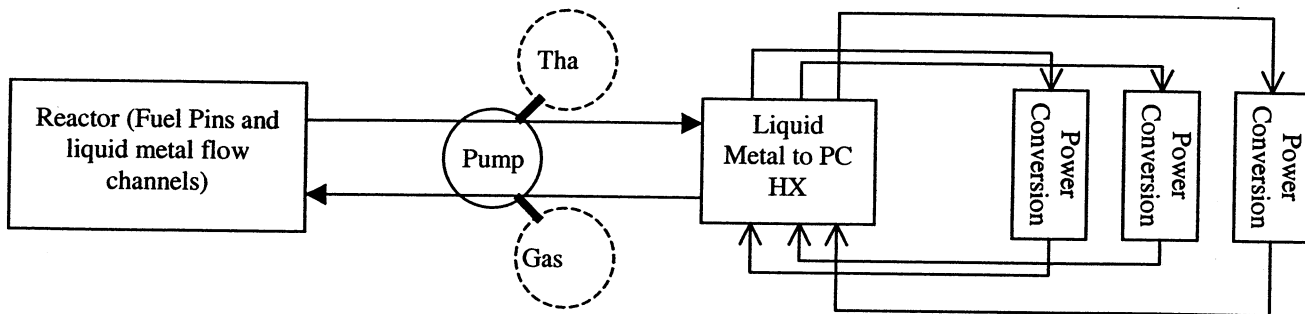


Figure 5. Schematic of the PLMR.

#### IV. COMPARISON OF FOUR SYSTEMS

The four systems were compared based on the following eight evaluation criteria: Vehicle System's Integration Interface, Safety, Reliability; Testability; Specific Mass; Cost; Schedule; and Programmatic Risk.

##### IV.A. Vehicle System's Integration

A preliminary comparison of vehicle systems integration issues is given in Table 2. Differences that have been identified include radiator area (primarily associated with

the choice of power conversion), structural / vibrational, and required power conditioning. Systems that utilize a Brayton cycle will require a larger radiator area than systems employing thermionic power conversion or other power conversion technologies that reject waste heat at high temperature. The potential for vibration also exists with dynamic power conversion systems, although there is confidence that vibrational issues can be resolved. As specific designs for each system mature, additional differences will be identified.

Table 2. Comparison of Vehicle System Integration Issues.

Concept	Radiator Size / temperature	Structural / Vibration	Power Conditioning	Effluents
Testable, passive, redundant reactor	230 m <sup>2</sup> , assuming 100 kWe, 25% efficient, 400 K effective radiator temp, 0.9 emissivity, 0 K sink.	Brayton Turbomachinery	Outputs high voltage AC	None or Option to vent non-condensable fission products
Testable multi-cell in-core thermionic system	18 m <sup>2</sup> , assuming 100 kWe, 10% efficient, 1000 K effective radiator temp, 0.9 emissivity, 0 K sink.	Pumped NaK No vibration from power conversion (static)	Outputs low voltage (100 V) DC	None or Option to vent non-condensable fission products
Direct gas-cooled reactor	230 m <sup>2</sup> , assuming 100 kWe, 25% efficient, 400 K effective radiator temp, 0.9 emissivity, 0 K sink.	Brayton Turbomachinery	Outputs high voltage AC	None
Pumped liquid metal reactor	230 m <sup>2</sup> , assuming 100 kWe, 25% efficient, 400 K effective radiator temp, 0.9 emissivity, 0 K sink.	Brayton Turbomachinery Pumped lithium	Outputs high voltage AC	None

#### IV.B. Safety

A preliminary comparison of system safety attributes is given in Table 3. Precluding inadvertent criticality appears to be the primary safety concern with developing and utilizing space fission systems. Arguments have been made that the low probability of launch accidents that could cause inadvertent criticality of a space fission system, coupled with the relatively low consequence of those accidents, reduces the need to design systems to ensure subcriticality during all credible launch accidents. However, recent policy dictates that precluding inadvertent criticality must be ensured. Inadvertent criticality must be precluded during all phases of testing, development, fabrication, launch, and (if applicable) earth re-entry. In addition to criticality safety, industrial hazards (such as hazardous or flammable materials) must be taken into account.

minimum amount of fabrication and handling occurs while the system is fueled. Systems designed to use "passive start" choose materials and geometry such that inadvertent criticality is precluded during all credible launch accidents. In addition to providing a reliability advantage, this approach eliminates the potential need for safety systems to be reversible in the event of a failed startup attempt and eliminates the need to ensure that the safety systems itself functions during all credible launch accidents. If extremely large shutdown margins are required, systems that allow in-space fueling or the use of retractable neutron absorbing wires may have an advantage. Retractable in-core shutdown rods are also an option for ensuring launch safety, although they have several disadvantages, including the requirement for shield penetrations and occupation of significant in-core volume. From a non-nuclear standpoint, systems that minimize hazardous material inventory or launch with hazardous materials in a favorable configuration have an advantage.

Designs that allow nuclear fuel to be removed or inserted as desired have a pre-launch safety advantage in that the

**Table 3. Comparison of System Safety Attributes**

Concept	Pre-Launch Nuclear Safety	Launch Nuclear Safety	Other Considerations
Testable, Passive, Redundant Reactor	Remove/insert fuel as desired for testing and handling.  Option for fueling at launch site or in-space.	"Passive start" approach facilitated by fast spectrum, pin-to-pin contact, high radial reflector worth.  In-space fueling option if extremely high shutdown margins desired.	Low liquid metal inventory.  Liquid metal launched in frozen state, contained in favorable geometry and independent containers (heat pipe wicks).
Testable Multi-Cell in-core Thermionic System	Remove/insert fuel as desired for testing and handling.  Option for fueling at launch site or in-space.	Evaluate safety effect of decreased radial reflector worth, increased core void fraction, and potential for reactor compaction.  Option for in-space fueling if extremely high shutdown margins desired.	NaK coolant in common superalloy or stainless steel vessel. Potentially launched in liquid state.
Direct Gas-Cooled Reactor	Fuel potentially sealed in core during reactor fabrication process.  Difficult to fuel at launch site or in space.	Evaluate safety effect of decreased radial reflector worth, increased core void fraction, and potential for reactor compaction.	He/Xe coolant is non-hazardous.
Pumped Liquid Metal Reactor	Fuel sealed in core during reactor fabrication process.  Difficult/impossible to fuel at launch site or in space.	Evaluate safety effect of decreased radial reflector worth, increased core void fraction, and potential for reactor compaction.	Contains a large volume of lithium coolant in common refractory metal vessel.

### IV.C. Reliability

A preliminary comparison of system reliability attributes is given in Table 4. Reliability related to five areas is evaluated: reactor start, heat transport, materials, power conversion, and overall system. Reactors able to use "passive start" as their safety approach will have an advantage in that the number of mechanisms that must properly function to allow system start will be minimized. Systems requiring in-core shutdown rods would need to be designed such that the rods are guaranteed to remain in the core during all credible launch accidents, but simultaneously have a highly reliable mechanism for extracting them once the desired operational orbit is achieved. Systems designed to use in-space fueling would require a highly reliable mechanism for inserting

the fuel, and systems designed to use retractable neutron absorbing wires would require a highly reliable mechanism for retracting those wires. The method chosen for primary heat transport can strongly effect system reliability. Heat pipes were chosen for the TPRR because they require no pumps, thaw systems, or gas separators; provide for passive removal of decay heat (as well as full power), and enable passive system restart. Cores that use only materials with demonstrated capability to withstand the in-core nuclear, thermal, electrical, and stress environment will have a reliability advantage. It is desirable for cores to be able to drive fully independent power conversion subsystems, and to be able to drive reliable auxiliary power systems. It is also desirable to eliminate single-point failures and reduce system complexity as much as possible.

**Table 4. Comparison of System Reliability Attributes.**

Concept	Reactor Start	Heat Transport	Materials	Power Conversion	System
Testable, Passive, Redundant Reactor	Baseline passive system start (no in-space fueling, no safety rod withdrawal).	Passive coolant thaw, passive full power primary heat transport, passive decay heat removal, passive restart.  No primary-side pumps, circulators, or moving parts.	Fluence, temperature, and burnup are within demonstrated capability of in-core materials.	Can drive fully independent power conversion subsystems.  Potential for reliable auxiliary power (e.g. thermoelectrics) driven by reactor.	No reactor-related single-point failures.  If desired, straightforward options for further increasing performance and redundancy.
Testable Multi-Cell in-core Thermionic System	If passive startup cannot be achieved, fuel must be inserted or shutdown rods withdrawn prior to start.	Pumped NaK loop for cooling (potential single-point failure).  Independent decay heat removal may be required if desired to prevent fuel damage following loss of NaK flow.	High temperatures (>1100 K) are confined to the fuel, clad, insulator, and emitter.  No refractory metals or exotic materials required for vessel, structure, radiators, etc.	Power conversion is highly redundant. Potential to design for graceful degradation.  Power conversion is static.  Lifetime of emitter trilayer.	Potential to keep NaK liquid throughout launch and mission.
Direct Gas-Cooled Reactor	If passive startup cannot be achieved, shutdown rods must be withdrawn prior to start.	Single Helium-Xenon pumped loop to cool the core (potential single point failure).  Independent decay heat removal system may be required if desired to prevent fuel damage following loss of gas circulation.	Design coolant gas flow path to reduce temperature of pressure-bearing structures to acceptable limits for non-refractory materials.	Same helium-xenon coolant flows through core and Brayton power converters. Leak or puncture in helium-xenon loop results in total system failure.  Debris/material from failed Brayton units, fuel pins, elsewhere, can be transported throughout system.	Cross-flow plenum may help enable realistic non-nuclear testing.  Potentially difficult to realistically test flight unit.
Pumped Liquid Metal Reactor	If passive startup cannot be achieved, shutdown rods must be withdrawn prior to start.	Single pumped lithium loop for cooling (potential single-point failure).  May require independent decay heat removal system.	Requires complex refractory metal pressure vessel.	Lithium / gas heat exchanger potential single point failure.  Potential for reliable auxiliary power (e.g. thermoelectrics) driven by reactor.	Microgravity lithium/helium gas separator. Lithium thaw system.  Very difficult to realistically test flight unit (lithium, pins).

#### IV.D. Testability

A preliminary comparison of system testability attributes is given in Table 5. Systems will not be able to rely solely on full power ground nuclear testing to resolve development issues. First, full power system ground nuclear tests cannot be performed on the actual flight unit because it would become radiologically activated and thus extremely difficult (impossible) to launch. Fabrication and other flaws associated with the flight unit would not be detected. Second, test facility requirements could lead

to significant design differences between the unit that was tested and the actual flight unit, severely limiting the value of the test. Third, full power system ground nuclear testing is extremely expensive and time consuming. Highly testable systems must allow very realistic non-nuclear simulation of nuclear heating to enable resolution of issues related to stress and heat transport. This requires ready access to the interior of the fuel clad, with minimal operations required to remove heaters, insert fuel, and ready the system for launch. The TPRR and TMCT both

**Table 5. Comparison of System Testability Attributes.**

Concept	Non-nuclear testing	Module testing	System complexity
Testable, Passive, Redundant Reactor	Verify heat transport and structural characteristics using resistance heaters to closely mimic heat from fission.  Realistic full-thrust testing of the actual flight unit.	System highly modular.  Resolve most potential issues at module level through nuclear and non-nuclear testing.	Fuel/heatpipe modules coupled to multiple ex-core heat exchangers.  System integration issues minimized. No in-core shutdown rods, pumps, microgravity gas separators, thaw systems, pressure vessels.  In-core materials operate within demonstrated capability (fluence, temperature, fuel burnup).
Testable Multi-Cell In-Core Thermionic Reactor	Verify heat transport and structural characteristics using resistance heaters to closely mimic heat from fission.  Realistic full-thrust testing of the actual flight unit.	Resolve technology issues (primarily fuel, emitter trilayer) via series of nuclear and non-nuclear tests. In-pile performance of trilayer is key.	Numerous (typically over 100) thermionic converters cooled by a pumped NaK loop. Potential system integration issues include the collector cooling loop, cesium reservoirs, and the electrical wiring of the core. Potential TMCT system-level nuclear issues may be challenging to resolve via non-nuclear testing.
Direct Gas-Cooled Reactor	Resistance heaters and wires to power heaters must be inserted through He/Xe plenum and potentially operate in He/Xe.  Full-thrust testing of actual flight unit may be difficult.	Noble gas coolant facilitates proper simulation of fuel-pin environment.  Nuclear / non-nuclear testing of fuel pins or fuel pin clusters.	Core and Brayton power conversion units share same helium/xenon coolant. Test effects of potential interactions.
Pumped Liquid Metal Reactor	Resistance heaters and wires to power heaters must be inserted through lithium plenum.  Full-thrust testing of actual flight unit does not appear feasible.	In-reactor (or resistance-heated) testing of pins or pin clusters in pumped lithium loop will be difficult.	Very difficult to perform realistic full-thrust testing of actual flight unit because of lithium distribution plenum, inaccessibility of fuel pins in assembled system, and the need to maintain high lithium purity. Difficult to test microgravity operation of lithium/helium separator. Oxidation sensitivity of Nb-1Zr increases test challenges.

provide ready access to the interior of the fuel clad. A testable DGCR may be feasible if a cross-flow plenum can be designed with acceptable pressure drop, and if stainless steel or superalloys can be used for the pressure boundary. Realistic testing of a PLMR system appears

extremely difficult because of the need to penetrate a lithium plenum and the need to maintain high purity lithium during the process of removing heaters and inserting fuel. Highly testable systems must also be modular enough to allow realistic testing of representative

modules in existing, operational test reactors. Testing required to resolve complex system integration issues can also be difficult to perform. Less complex systems have a testability advantage. In-pile testing of emitter trilayers operating at  $>1800$  K with a prototypic voltage gradient across the insulator would be required for the development of the Testable Multi-Cell In-Core Thermionic Reactor. These tests could be difficult to perform.

#### IV.E. Specific Mass

Preliminary comparison of reactor specific mass attributes is given in Table 6. Although reactor specific mass is important, preliminary studies indicate that the reactor, shield, and primary heat transport system will only account for 1/3 of the total NEP system mass. Roughly  $\frac{1}{2}$  of the mass will be associated with power conversion,

power conditioning, and heat rejection, and 1/6 associate with the electric thrusters. An important attribute associated with specific mass is thus the ability to provide thermal power to the power conversion subsystem at the maximum usable temperature. Within the reactor itself, specific mass is reduced by increasing the core fuel fraction (thus decreasing core and shield size) and minimizing components needed for system integration and operation. The DGCR has a potential specific mass advantage because it eliminates the need for an ex-core heat exchanger. However, this advantage may be offset by increased void space within the core. The TMCT has a potential specific mass advantage because power conversion occurs within the core and waste heat is rejected at a very high temperature. Detailed designs with consistent technology and safety assumptions will be required to determine the minimum specific mass reactor design.

**Table 6. Comparison of System Specific Mass.**

Concept	Drivers	Savings	Systems Integration
Testable, Passive, Redundant Reactor	Provides power at high temperatures driving state-of-the-art and near-term power conversion subsystems (i.e. Brayton).	High core fuel fraction helps reduce core volume and shield mass.  Passive start option eliminates mass penalty from in-core shutdown rods.  Jettisonable in-space fueling mechanism option would provide mass savings but with potential reliability penalty.	Relatively few components required for system integration. Design eliminates need for reactor coolant pumps, thaw systems, in-core shutdown rods, decay heat removal systems, gas separators, and other components.
Testable Multi-Cell In-Core Thermionic System	TMCT provides both energy and power conversion.	Combined nature of reactor and power conversion subsystem. Eliminate high temperature primary heat transport system, reactor to power conversion heat exchanger.  Ability to radiate waste heat at high temperature (1000 K) reduces radiator size an order of magnitude.	Output is relatively low voltage (100 V) DC. Power conditioner will be different than that needed by high voltage Brayton.  Integration issues associated with combined core/power conversion system may result in mass penalty.
Direct Gas-Cooled Reactor	Reactor core serves as both energy source and gas heat exchanger.	In-core fuel pin to gas heat exchange eliminates separate core to power conversion system heat exchanger.  Single coolant loop may provide mass savings but potential reliability penalty.	Decreased reactor fuel fraction, decay heat removal system, and in-core shutdown rods may increase reactor and shield mass.
Pumped Liquid Metal Reactor	Core cooled by pumped lithium loop, launched frozen, thaw in space.		Mass penalty from complex integration issues associated with in-core shutdown rods (if needed), lithium thaw system, lithium/helium gas separator, and EM pumps, all with a refractory metal vessel.

#### IV.F. Schedule, Cost, Programmatic Risk

A preliminary comparison of reactor schedule, cost, and programmatic risk is given in Table 7. The schedule for all of the systems could be driven by the nuclear testing required by that concept. This includes component tests in operational reactors as well as full power system ground nuclear testing. From a schedule, cost, and programmatic risk standpoint there is strong incentive to design systems such that a full power ground nuclear system test is not required for flight qualification. This would require that a suitable combination of non-nuclear testing, zero-power critical experiments, and in-pile

module tests be devised to provide high confidence in system safety and reliability. The cost estimates for the TPRR and the PLMR are for the reactor only. The cost estimate for the TMCT is based on previous studies and personal communications and needs to be updated. The TMCT cost estimate includes both the reactor and power conversion subsystem. The cost estimate for the DGCR is for the full-up NEP system. Programmatic risk is reduced if the system couples well to more than one type of power conversion subsystem (program success is not totally dependent on successful development of a specific power conversion option). Programmatic risk is also reduced if

**Table 7. Comparison of Schedule, Cost, and Programmatic Risk.**

Concept	Schedule	Cost	Programmatic Risk
Testable, Passive, Redundant Reactor	Realistic resistance-heated testing, simplicity, modularity, reduced system integration all shorten schedule.  In-reactor module testing / post irradiation examination (PIE) may be schedule driver.	\$210M - \$250M (FY02) to develop reactor. Comprehensive bottoms-up estimate (LANL FY01).	Core suitable for providing energy to different types of power conversion subsystems for both primary and emergency power.  Significant hardware-based milestones early in program.
Testable Multi-Cell In-Core Thermionic System	Development, in-reactor testing, and PIE of fueled emitter trilayer may drive schedule.  Schedule benefit from realistic resistance-heated testing.  Schedule concern if multiple iterations of in-pile testing required to develop emitter trilayer.	Entire TMCT power system (including power conversion and radiator, in addition to the reactor) potentially less than \$800M to develop. DOE 40 kWe Thermionic Reactor Studies (early 1990s).	Development and testing of long-life thermionic converters may be difficult.  Only suited for thermionic power conversion.  Static power conversion / no need for separate power conversion subsystem.  Option (if desired) for reduced-enrichment uranium fuel.
Direct Gas-Cooled Reactor	Potential difficulty in performing realistic resistance-heated testing may lengthen schedule.  In-reactor testing of fuel pins or representative fuel pin clusters.  Advocates recommend full-power ground nuclear test.	Cost estimate for >300 kWe NEP system potentially available from Intraspace Corporation.	Advocates recommend full-power ground nuclear test.  System suitable primarily for Brayton power conversion subsystem.  Reactor / power conversion gas loop is single-point failure.
Pumped Liquid Metal Reactor	Difficulty in performing realistic resistance-heated testing may lengthen schedule.  In-reactor testing of fuel pins or fuel pin clusters in a pumped lithium loop will be difficult.  Previous program (SP-100) baselined full-power ground nuclear test.	FY01 DOE estimate \$540M to develop reactor.	Core suitable for providing energy to different types of power conversion subsystems for both primary and emergency power.  Directly draw on lessons learned from 11 year, \$0.5B SP-100 program.  System complexity and system testability.  Potential need for ground nuclear test.

significant early milestones can be achieved. Designing the system to reduce/eliminate the need for a full power ground nuclear system test also reduces programmatic risk.

It is important to note that all four systems deviate substantially from reactors previously used terrestrially or in space. Although heatpipes have been used extensively in-core, they have never been used as the primary means of heat transport out of a reactor. Russian thermionic systems have flown in space, but there are concerns surrounding their lifetime potential. Additionally, there is little US infrastructure for thermionic systems, and the system evaluated would require development of an advanced emitter trilayer. Terrestrial gas-cooled reactors (e.g. Fort St. Vrain) typically have not used pin fuel or refractory metal fuel clad, have not operated at the temperatures required by the Phase 1 system, and have utilized a thermal neutron spectrum. Direct gas-cooled space reactors would thus be significantly different than terrestrial gas-cooled systems. Liquid metal cooled terrestrial reactors (e.g. FFTF, EBR-II) have not used lithium coolant, have not used refractory metal fuel clad/vessels, have not used EM pumps, have not operated in zero gravity, and have not operated at the temperatures required by Phase 1 fission electric propulsion systems. The PLMR is thus significantly different from terrestrial liquid metal cooled reactors. A certain level of programmatic risk exists for all options because they deviate from systems for which operational experience exists.

## V. OBSERVATIONS

All four of the systems evaluated could potentially be developed for use on NEP missions. However, the likelihood of program success can be greatly increased via proper choice of the reactor subsystem. In general, choosing the least expensive, shortest schedule approach that meets all mission requirements will be needed to ensure successful utilization. Important reactor

evaluation criteria include system integration, safety, reliability, testability, specific mass, cost, schedule, and programmatic risk. Updated comparisons should be performed as specific system designs mature.

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